Mirror Technology Roadmap for NASA's Exoplanet Exploration Program

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Exoplanet Exploration Program Chief Technologist

with

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Jet Propulsion Laboratory

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Mirror Technology SBIR/STTR Workshop,

Greenbelt, Maryland, USA

21 June 2011

ExoPlanet Exploration Program

- Direct detection of terrestrial planets in the habitable zone around nearby stars

- Characterization of planetary atmospheres in search of the signatures of life

- Direct detection and characterization of other constituents of planetary systems

- Revolutionary general astrophysics investigations

  - **Direct detection** - *must separate planet light from star light*

  - **Planet characterization** - *must determine type of planet, its gross physical properties and atmosphere constituents* allowing *assessment of likelihood of life*

Gliese 229 a

Gliese 229 b

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995
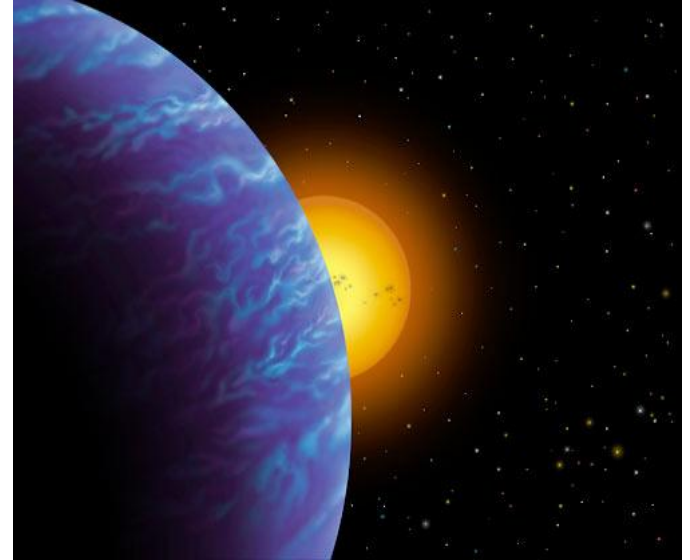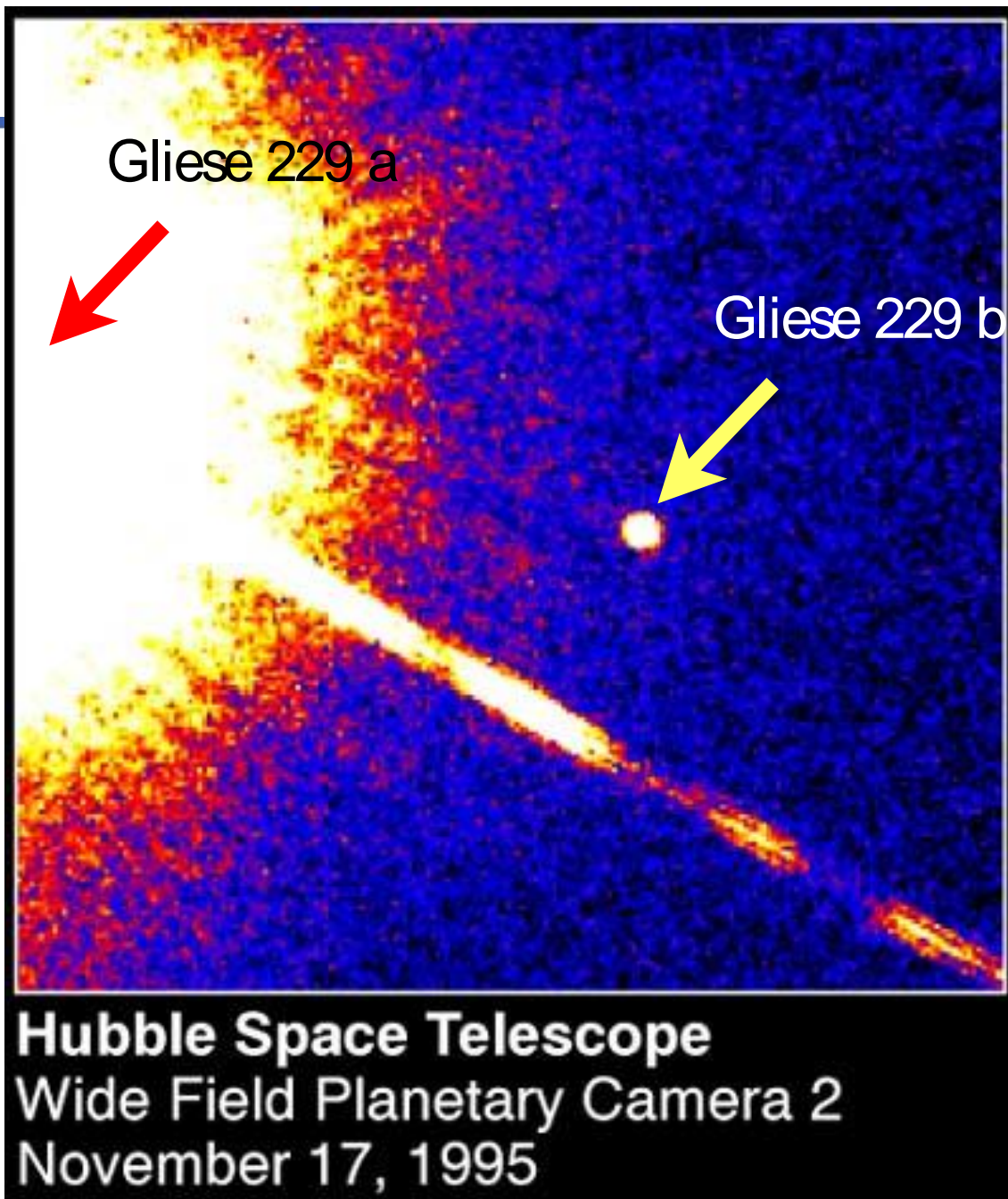
Brown Dwarf
44 AU
20-50 M_J

Discovered
1995

Starlight suppression allows the *spectra* of planets to be detected
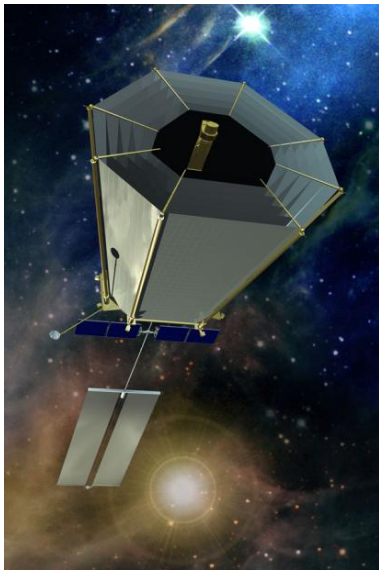
2.4-m telescope

50 mas resolution

ExoPlanet Exploration Program

ExoPlanet Exploration Program

At mid-infrared wavelengths, exoplanets shine because they are warm

At visible wavelengths, exoplanets shine in reflected starlight

$\lambda \ (\mu m)$
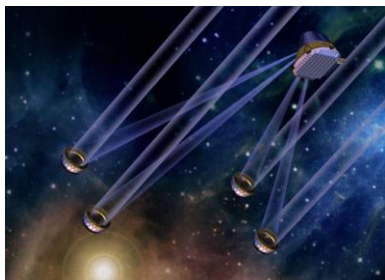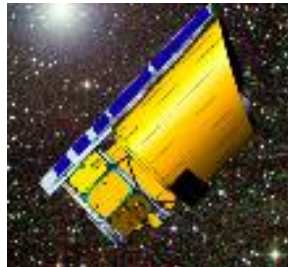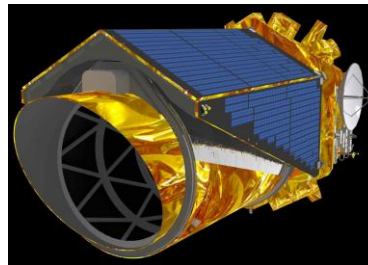
ExoPlanet Exploration Program

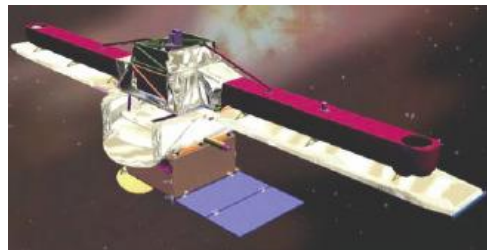**TPF-C** Terrestrial Planet Finder Coronagraph

TPF-I Terrestrial Planet Finder Interferometer
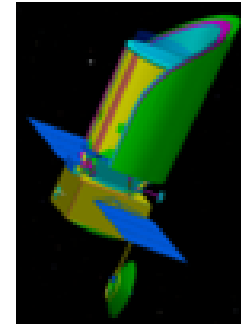
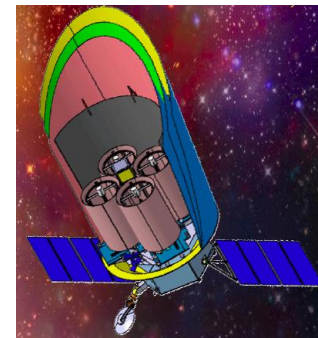**PECO** Pupil-Mapping Exoplanet Coronagraphic Observe

EPIC Extrasolar Planetary Imaging Coronagraph
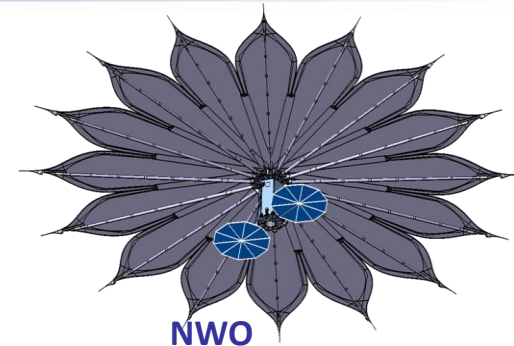
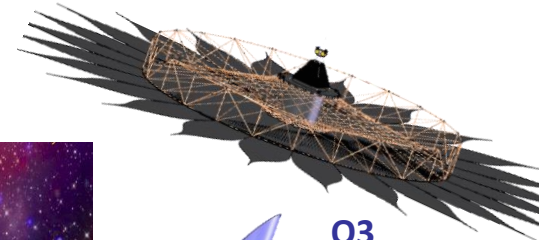**FKSI** Fourrier-Kelvin Stellar Interferometer

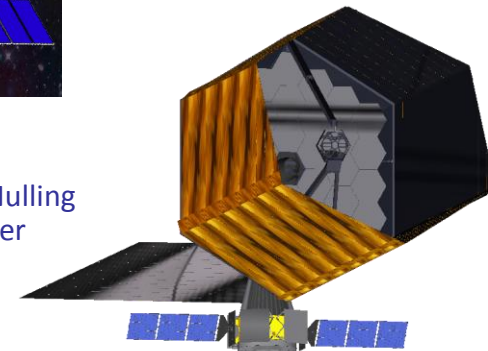**ACCESS** Actively-Corrected Coronagraph for Exoplanet System Studies

DAViNCI Dilute Aperture Visible Nulling Coronagraph Imager
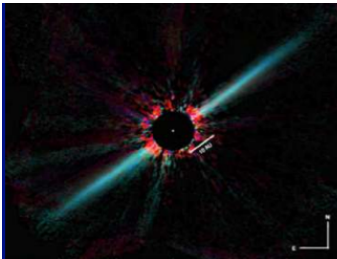
NWO New Worlds Observer

O3 Occulting Ozone Observatory

ATLAST Advanced Technology Large-Aperture Space Telescope

ExoPlanet Exploration Program

#1 Priority for Medium-scale space program

New Worlds Technology Development Program

- To achieve New Worlds objective – studying nearby, habitable exoplanets - need **preliminary observations** before choosing a flagship mission:

  – Planetary demography over wide range of conditions:
    ▪ Kepler, WFIRST, integrated ground-based program

  – Measurement of zodiacal light:
    ▪ Ground-based telescopes.
    ▪ Sub-orbital and explorer mission opportunities.

- In parallel, need **technology development** for competing approaches to make informed choice in second half of decade

- **RECOMMEND $100-200M over decade**

- Planned integrated ground-space exoplanet program
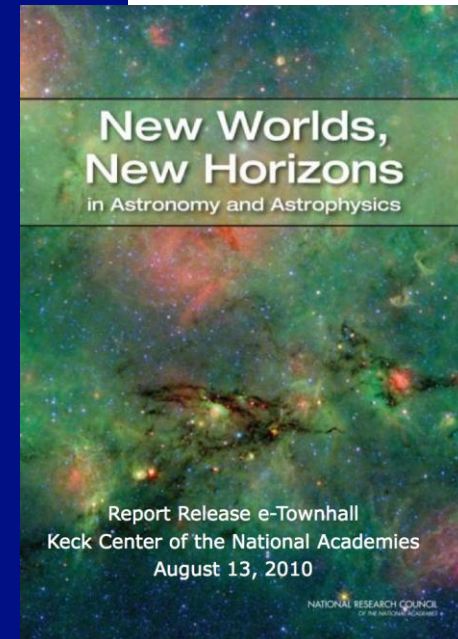
New Worlds, New Horizons in Astronomy and Astrophysics

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES   30
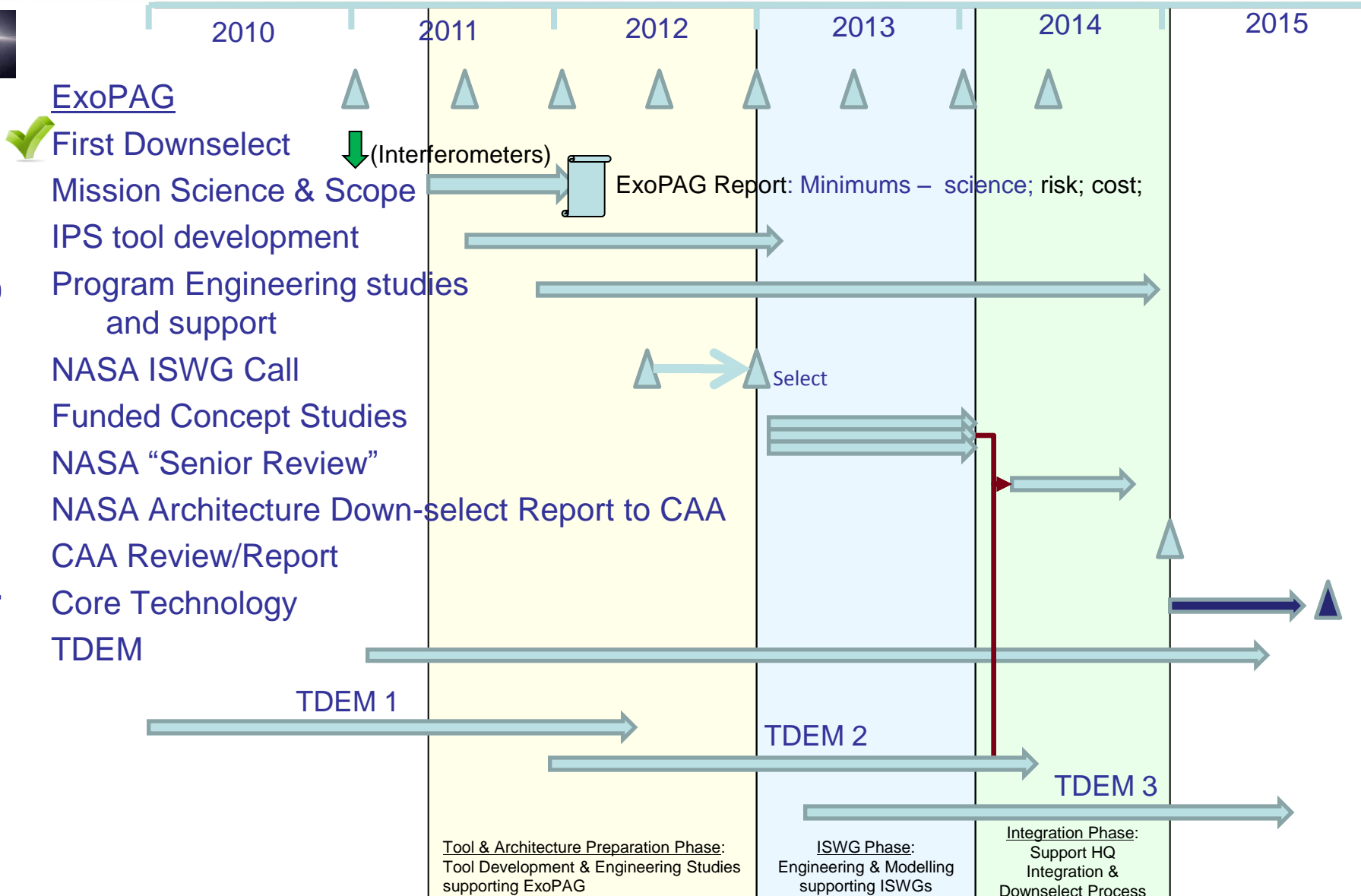
New Worlds, New Horizons in Astronomy and Astrophysics

Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

National Research Council of the National Academies

Concept Studies and Architecture Selection for a *New Worlds Mission*

Timeline (2010–2015) for the ExoPlanet Exploration Program:

- **ExoPAG**
- **First Downselect** — (Interferometers)
- **Mission Science & Scope** — ExoPAG Report: Minimums – science; risk; cost;
- **IPS tool development**
- **Program Engineering studies and support**
- **NASA ISWG Call** — Select
- **Funded Concept Studies**
- **NASA "Senior Review"**
- **NASA Architecture Down-select Report to CAA**
- **CAA Review/Report**
- **Core Technology**
- **TDEM**
  - **TDEM 1**
  - **TDEM 2**
  - **TDEM 3**

Tool & Architecture Preparation Phase: Tool Development & Engineering Studies supporting ExoPAG

ISWG Phase: Engineering & Modelling supporting ISWGs

**Integration Phase:** Support HQ Integration & Downselect Process

ExoPlanet Exploration Program

- Wavelength range: 3-8 microns, 6-18 microns
- Cryogenic optics, diffraction limited
- Primary mirrors (0.5–2-m diameter) of beryllium or silicon carbide
- Cryogenic deformable mirrors for wave-front correction
- Cryogenic delay-lines and fine-steering mirrors
- Mid-infrared single-mode fiber optics
- Cryocoolers for detectors
- Passive cooling of optics to 35–40 K
- Formation flying
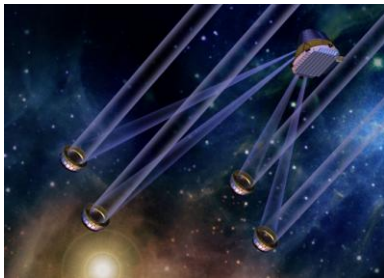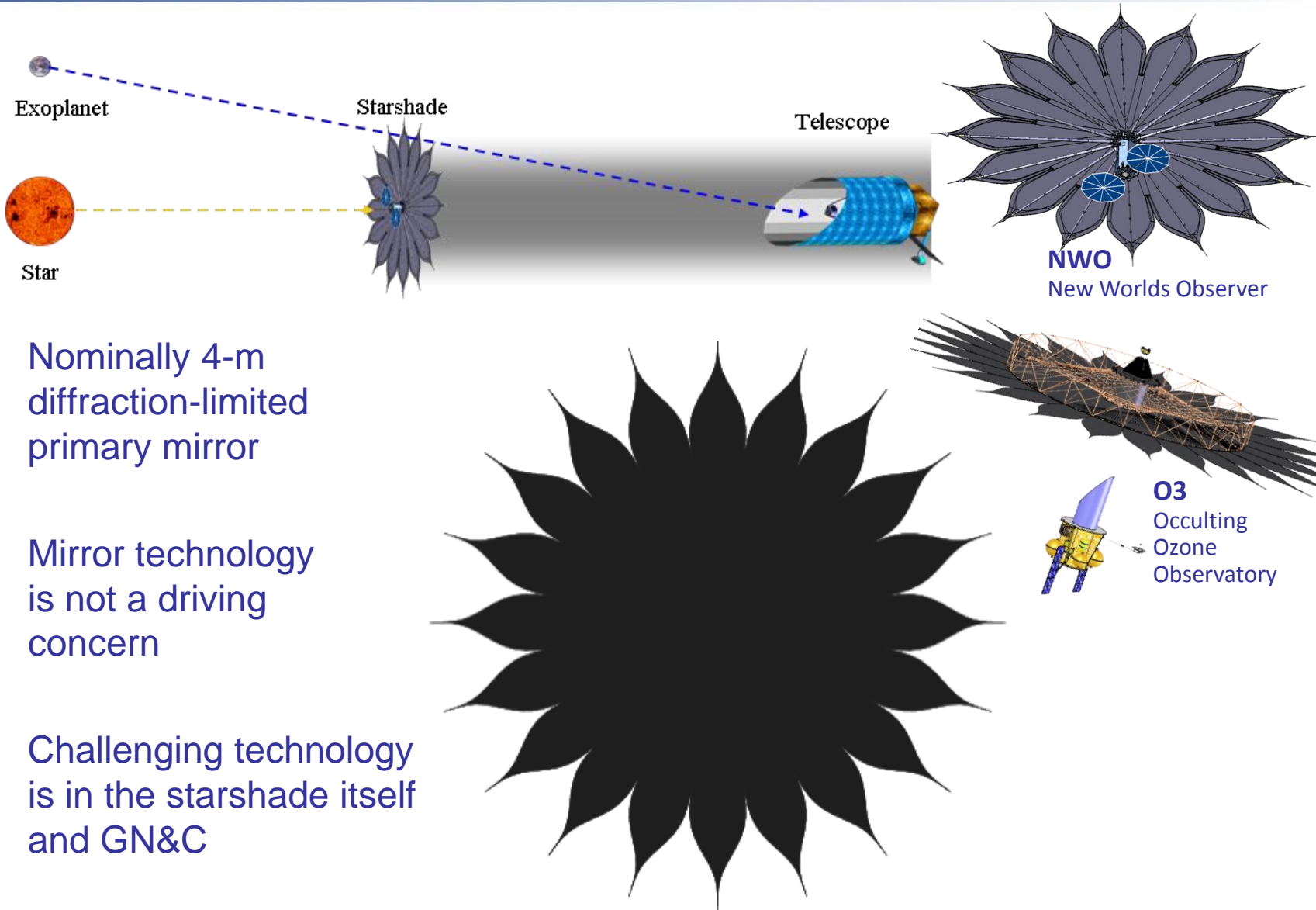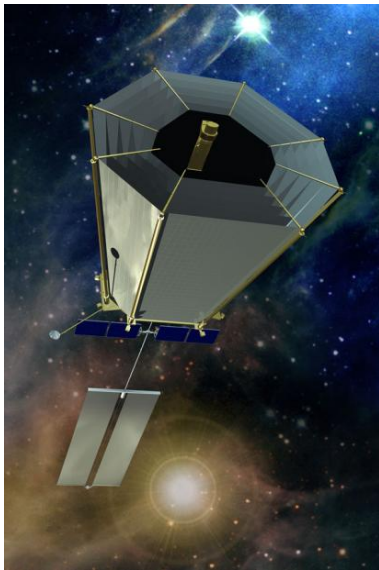
TPF-I Terrestrial Planet Finder Interferometer
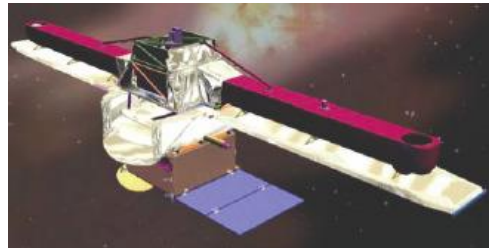
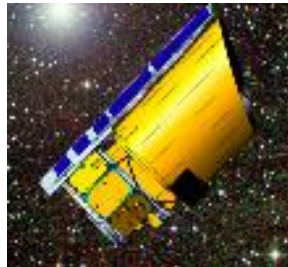**FKSI** Fourier-Kelvin Stellar Interferometer

Research slowed or halted
Low-priority for NASA funding

ExoPlanet Exploration Program

Courtesy of Amy Lo, Northrup Grumman Space Corp.

Exoplanet

Star

Starshade

Telescope

NWO
New Worlds Observer

O3
Occulting Ozone Observatory

- Nominally 4-m diffraction-limited primary mirror

- Mirror technology is not a driving concern

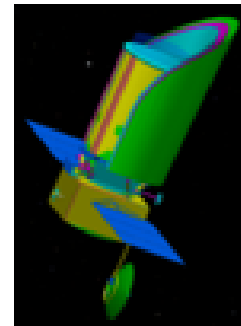- Challenging technology is in the starshade itself and GN&C

ExoPlanet Exploration Program
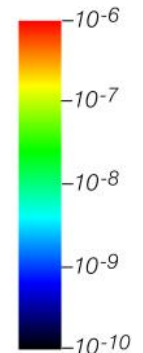

TPF-C Terrestrial Planet Finder Coronagraph

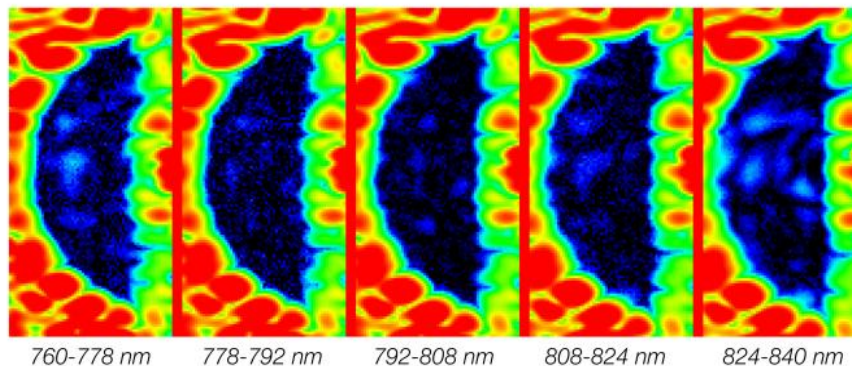**PECO** Pupil-Mapping Exoplanet Coronagraphic Observe

ACCESS Actively-Corrected

Xinetics Inc (NGAS)

Unobscured Primary

Cassegrain Secondary

Image 1

DM Collimator

DM (Wavefront Correction)

DM Camera

Image 2

Collimator

Lyot Stop

Science Focus Camera

Image 3

Occulting Spot

Science Camera

Wavefront Corrector

Coronagraph

Outer dark field

Star

Inner dark field

760-840 nm   760-778 nm   778-792 nm   792-808 nm   808-824 nm   824-840 nm

-10^{-6}
-10^{-7}
-10^{-8}
-10^{-9}
-10^{-10}

ExoPlanet Exploration Program

Magellan

HST

Kodak
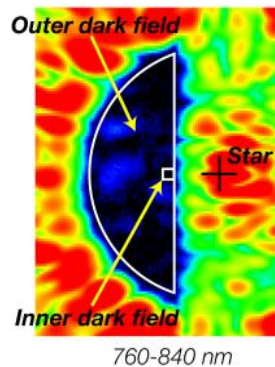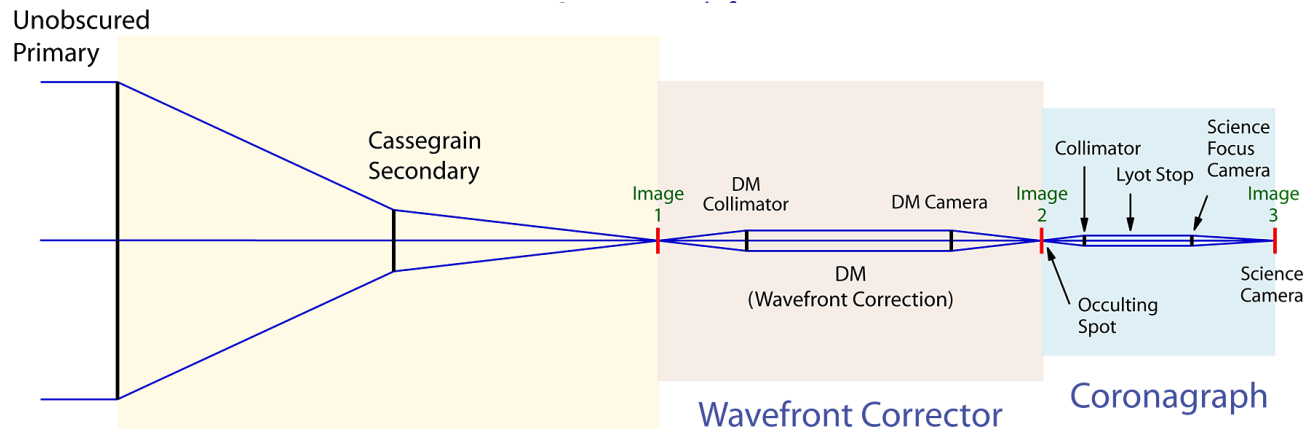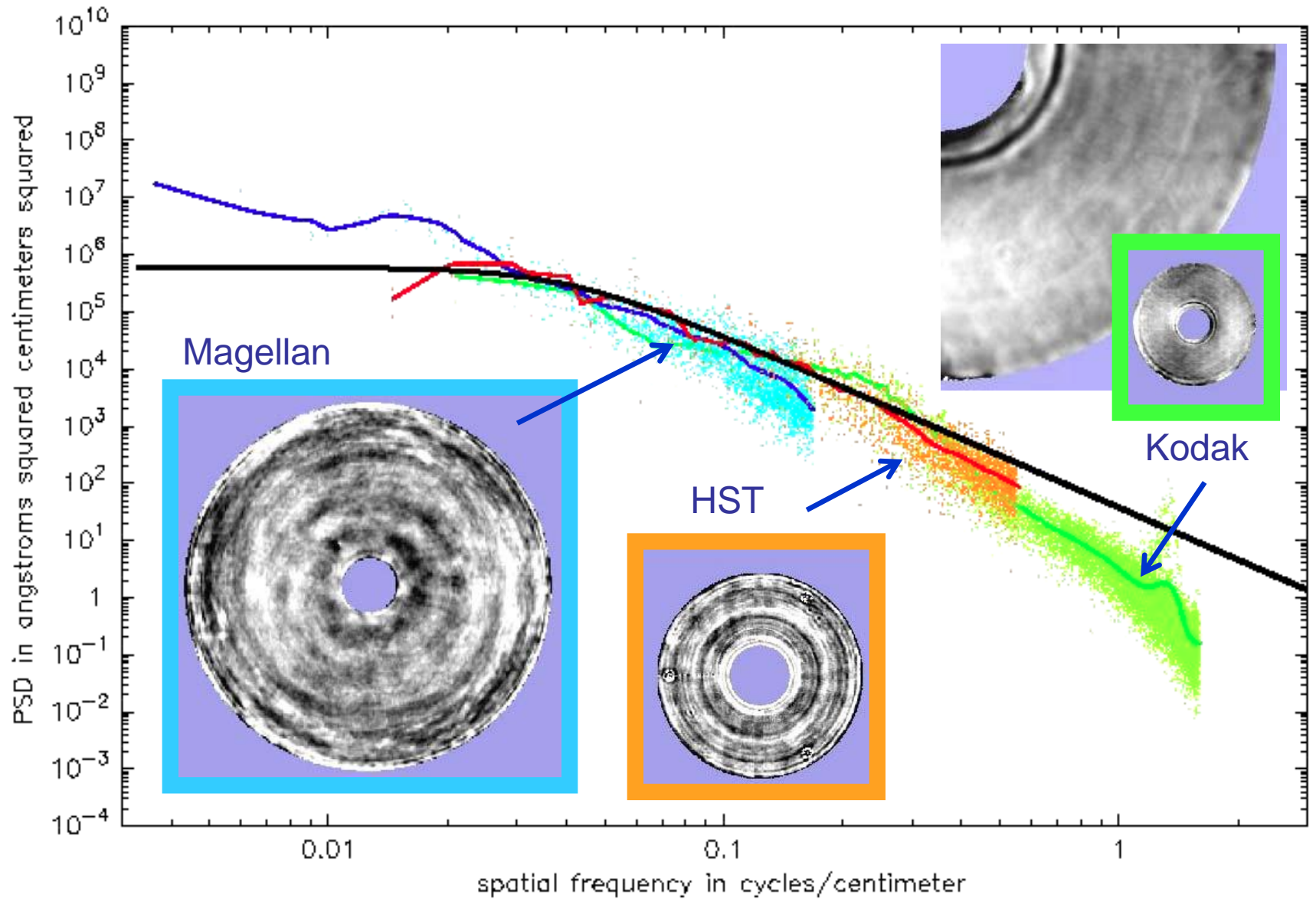
Original from T. Hull and J. Trauger

ExoPlanet Exploration Program

TDM Baseline Concept

- 1.9-m diameter, off-axis segment
- Surface errors < 5 nm rms in mid-spatial frequencies
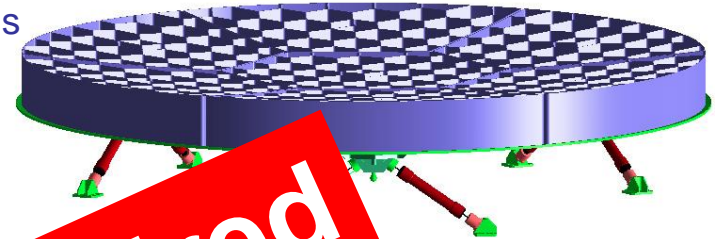- Areal density of 47.5 kg/m^2 (60 kg/m^2 required)
- Advanced waterjet lightweighted
- ULE glass
- On orbit PV quilting < 1mn

Parameter	Range		Goal
SURFACE ERROR REQUIREMENTS			
Low Spatial Frequency	< 0.	10 nm rms	5 nm rms
Mid Spatial Frequency	0.025- cycles/cm	5 nm rms	2.5 nm rms
High Spatial Frequency	0.5-10 cycles/cm	1.4 nm rms	0.7 nm rms
Micro-roughness	> 10 cycles/cm	10 Å rms	5 Å rms
COATING RESIDUAL REFLECTANCE REQUIREMENTS			
Mid Spatial Frequency	0.025-0.5 cycles/cm	< 0.3% rms	≤ 0.1 % rms

Not Required

The revised HST-like surface requirements for a TPF-C are described in the following paper:
S. B. Shaklan, J. J. Green, D. M. Palacios, "The Terrestrial Planet Finder Coronagraph Optical Surface Requirements," Proc. SPIE 6265, 62651L (2006).

ExoPlanet Exploration Program

PM shape: (Thermal and Jitter)
$z4=z5=z6=z8=z10=0.4$ nm
$z7=0.2$ nm, $z11=z12=5$ pm

Secondary:
Thermal: $\Delta x=65$ nm,
$\Delta z=26$ nm,
tilt=30 nrad
Jitter: 20x smaller

Laser metrology:
$\Delta L=25$nm
$\Delta f/f=1\times10^{-9}$

Fold mirror 1:
rms static surf =0.85nm
Thermal: 10nrad, 100 nm
Jitter: 10 nrad, 10 nm

Mask centration:
offset=0.3 mas
amplitude=0.3mas

Mask error = 5e-4
at 4 λ/D
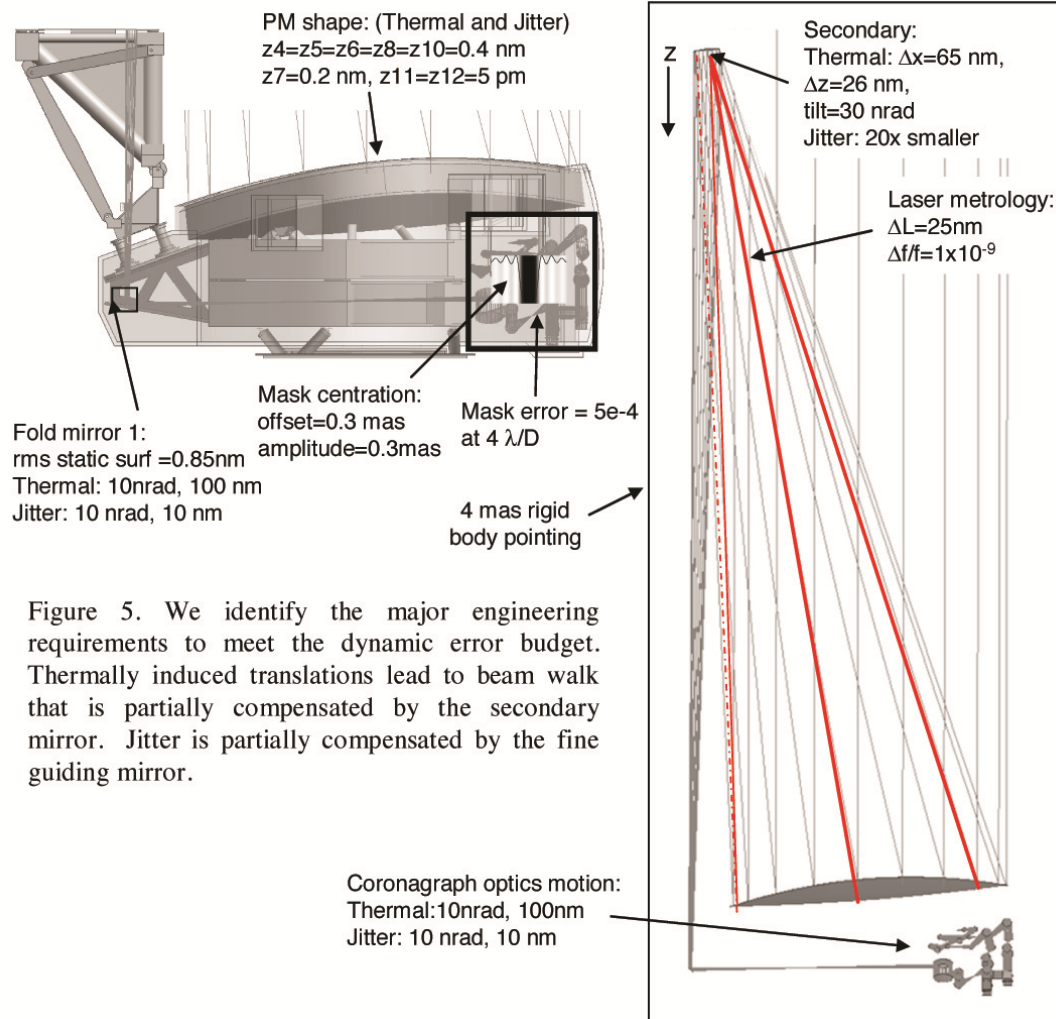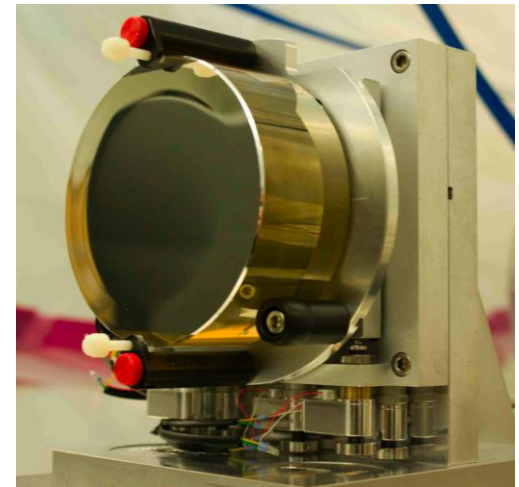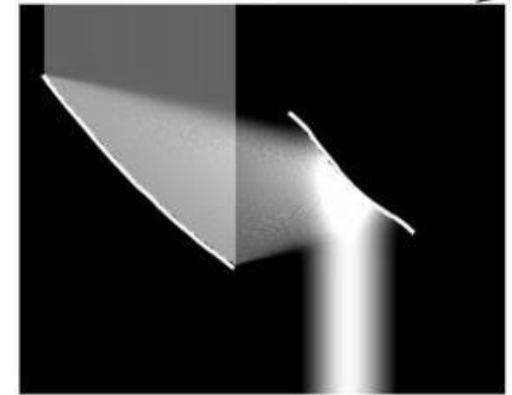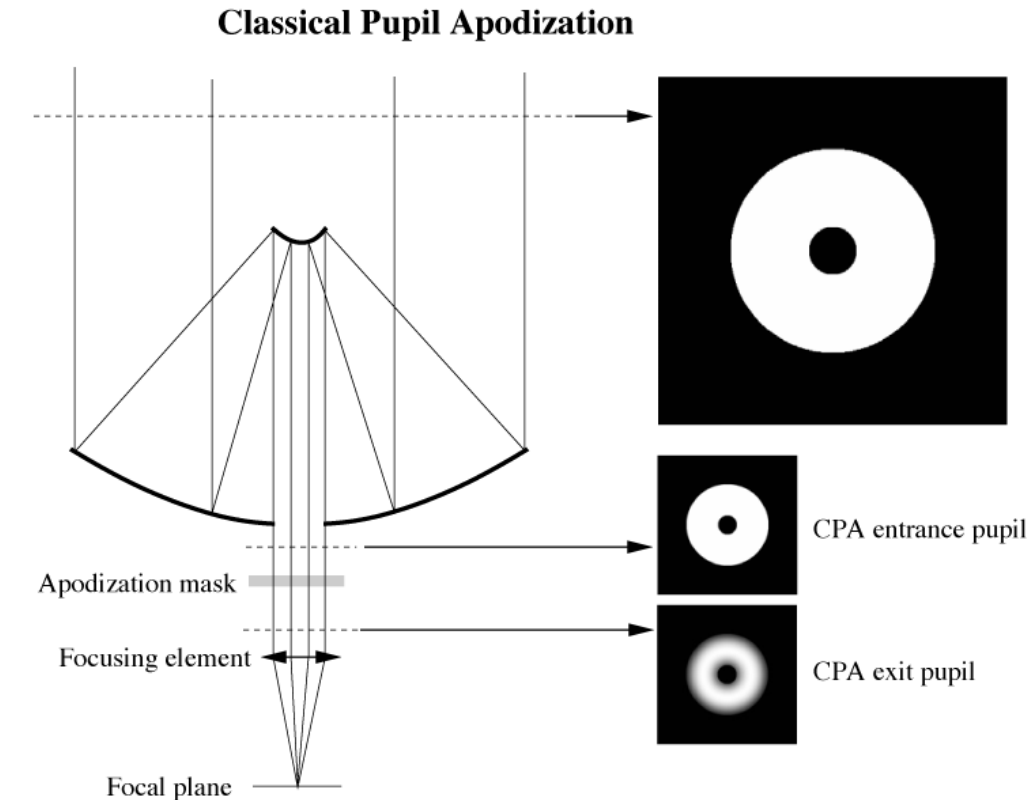
4 mas rigid
body pointing

Figure 5. We identify the major engineering requirements to meet the dynamic error budget. Thermally induced translations lead to beam walk that is partially compensated by the secondary mirror. Jitter is partially compensated by the fine guiding mirror.

Coronagraph optics motion:
Thermal:10nrad, 100nm
Jitter: 10 nrad, 10 nm

Laser metrology required for sensing and control

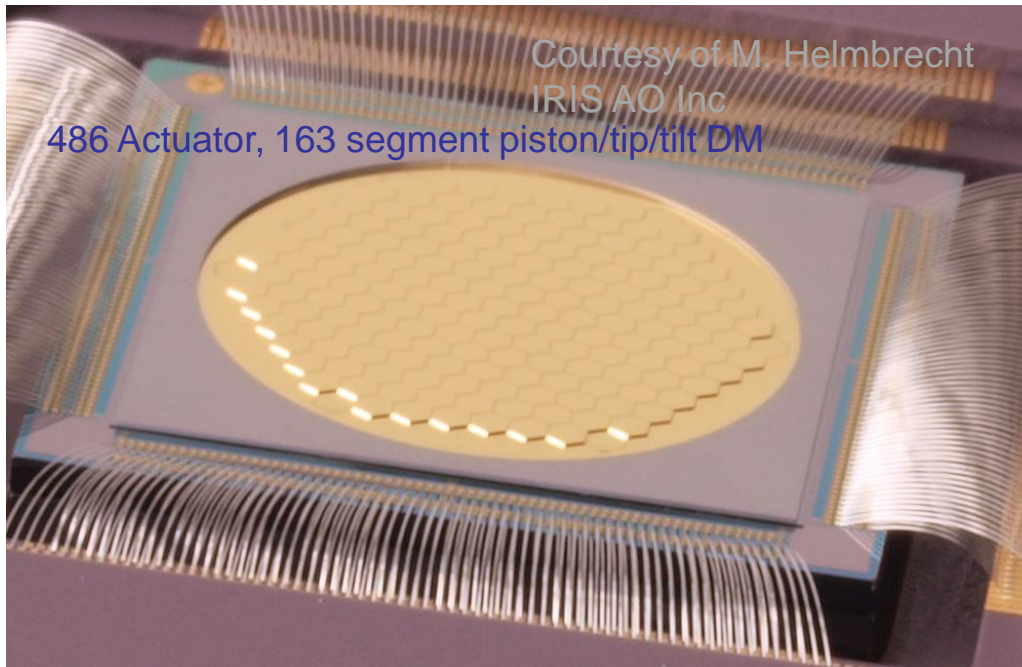Key requirements 1–2 orders of magnitude tighter for a 3.8-m telescope operating at 2λ/D

S. B. Shaklan, L. Marchan, J. J. Green, O. P. Lay, "Terrestrial Planet Finder Coronagraph Dynamics Error Budget," Proc. SPIE 5905 (2005).

S. B. Shaklan, L. F. Marchan, J. E. Krist, M. Rud, "Stability error budget for an aggressive coronagraph on a 3.8-m telescope," Proc. SPIE 8151, San Diego, August 2011.
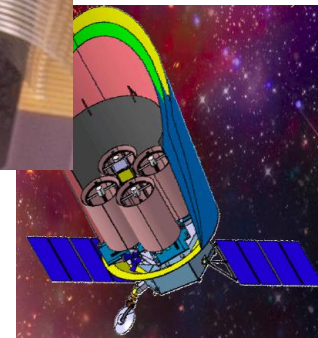
ExoPlanet Exploration Program

Classical Pupil Apodization
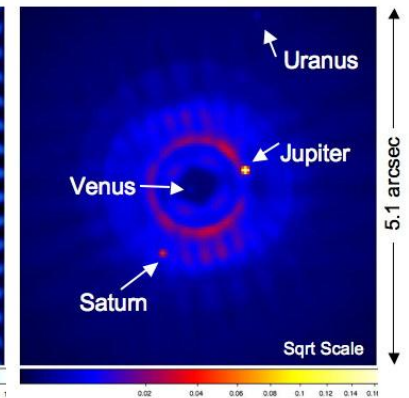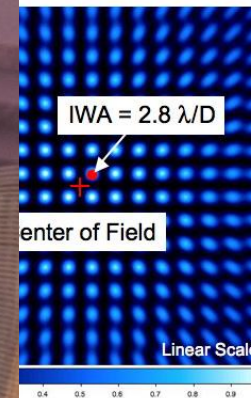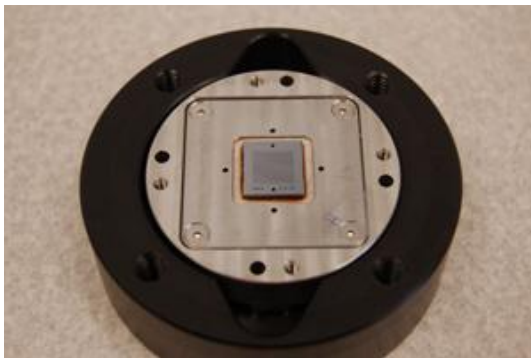
CPA entrance pupil

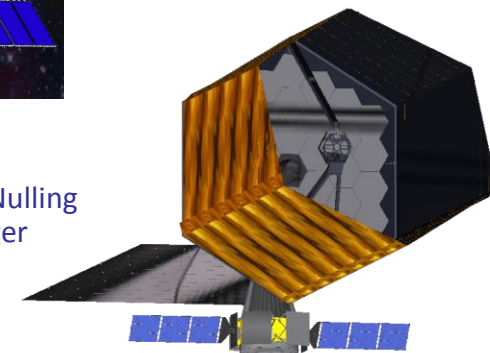CPA exit pupil

Tinsley Laboratories

O. Guyon, S. Shaklan, M. Levine, et al. "The Pupil mapping Exoplanet Coronagraphic Observer," Proc. SPIE 7731, 77319 (2010)

ExoPlanet Exploration Program

Courtesy of M. Helmbrecht
IRIS AO Inc

486 Actuator, 163 segment piston/tip/tilt DM

IWA = 2.8 λ/D

Center of Field

Linear Scale

Uranus

Jupiter
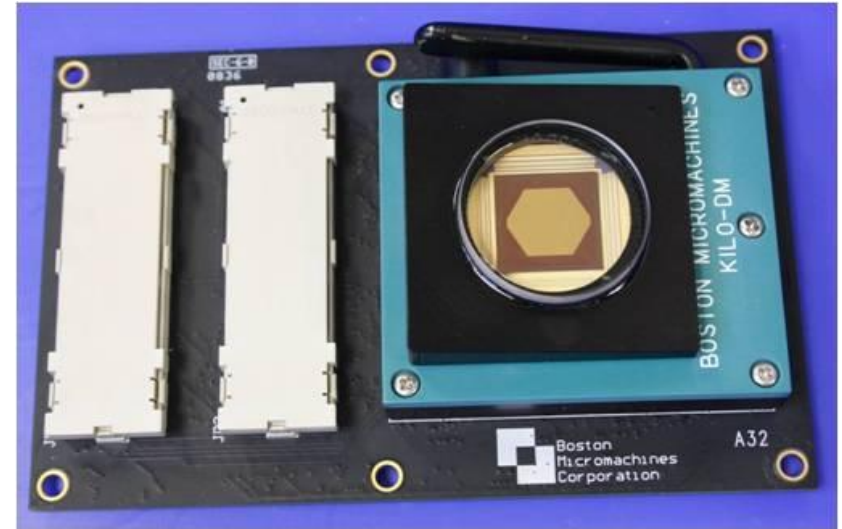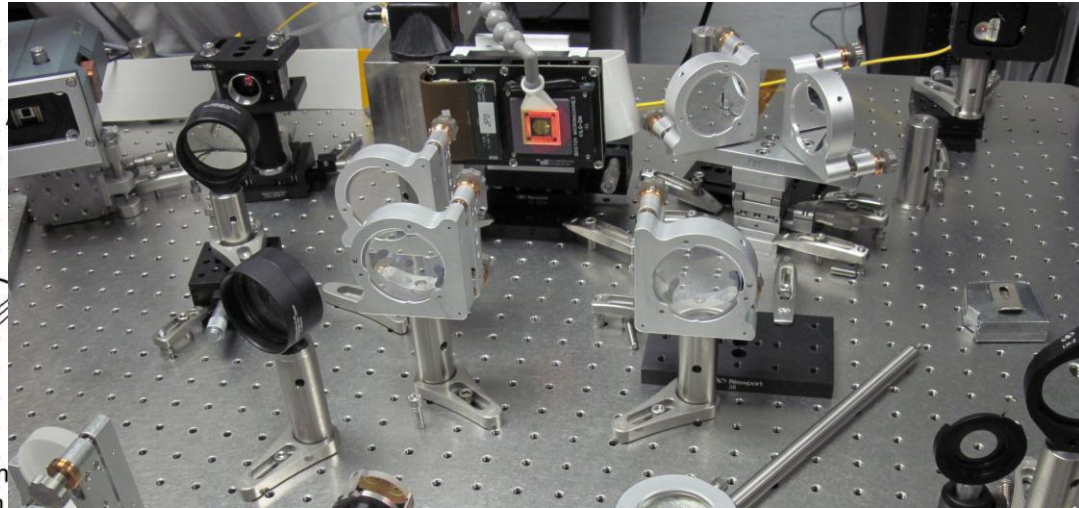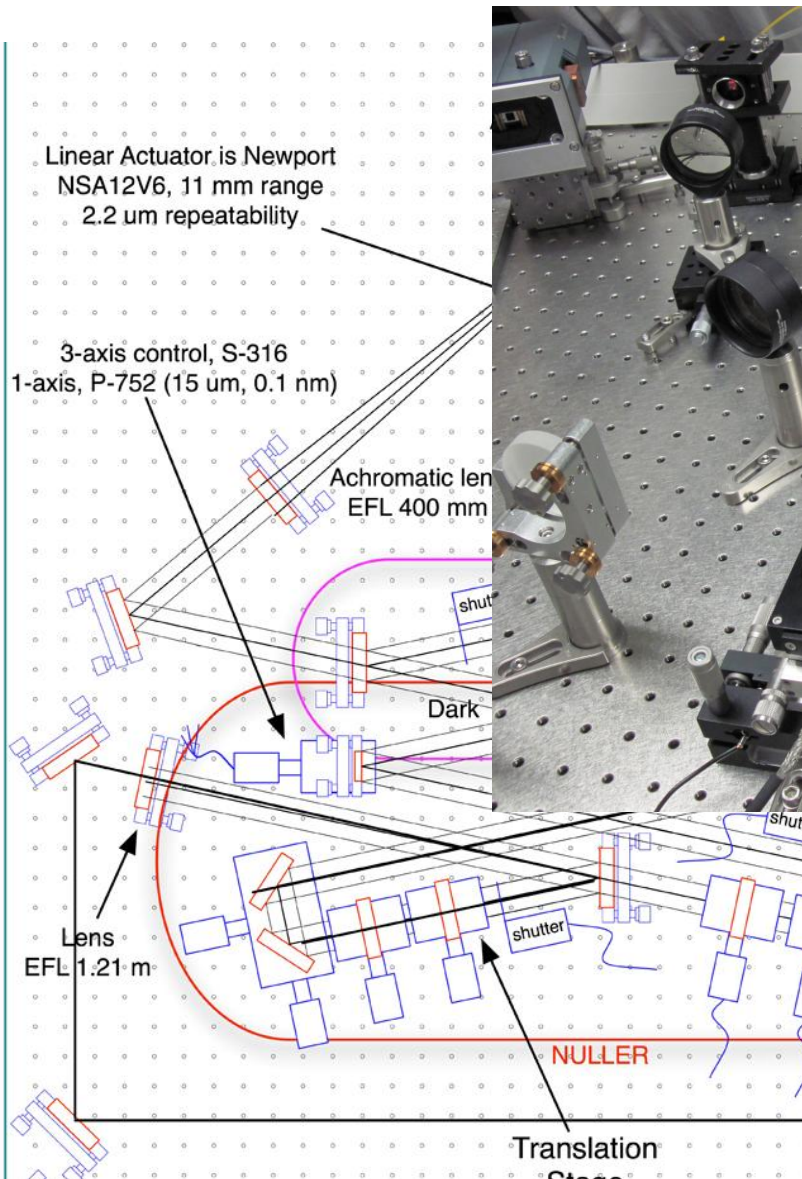
Venus

Saturn

Sqrt Scale

5.1 arcsec

EPIC Extrasolar Planetary Imaging Coronagraph

DAViNCI Dilute Aperture Visible Nulling Coronagraph Imager

ATLAST Advanced Technology Large-Aperture Space Telescope

ExoPlanet Exploration Program

Linear Actuator is Newport
NSA12V6, 11 mm range
2.2 um repeatability

3-axis control, S-316
1-axis, P-752 (15 um, 0.1 nm)

Achromatic lens
EFL 400 mm

shutter

Dark

Lens
EFL 1.21 m

shutter

shutter

NULLER

Translation
Stage

331 segment piston/tip/tilt DM

Courtesy of T. Bifano, Boston Micromachines

ExoPlanet Exploration Program

PECO Pupil-Mapping Exoplanet Coronagraphic Observe

ACCESS Actively-Corrected Coronagraph for Exoplanet System Studies

NWO New Worlds Observer

TPF-C Terrestrial Planet Finder Coronagraph

EPIC Extrasolar Planetary Imaging Coronagraph

O3 Occulting Ozone Observatory

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ExoPlanet Exploration Program
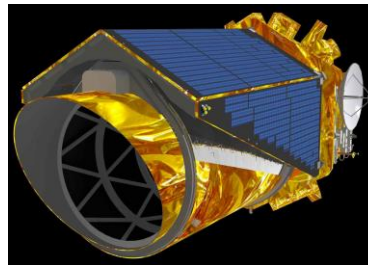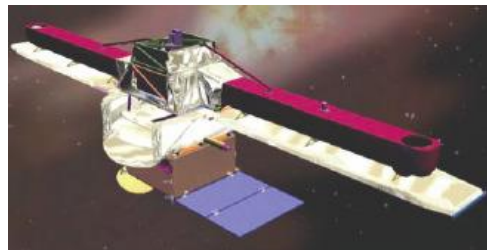
- Coronagraph
  - Starlight entering the telescope must be suppressed
  - Diffraction artifacts must be controlled or mitigated
    - Off-axis un-obscured aperture design
    - Coronagraphic masks
    - Deformable mirrors

- Visible Nulling Coronagraph
  - Similar constraints as above
  - Instrument is an interferometer
  - Well suited for use with segmented-mirror telescopes, yet with extremely challenging requirements

- Starshade
  - Starlight never enters the telescope – no scattered light to suppress
  - Diffraction effects are controlled by the shape of the starshade
    - The telescope must be diffraction limited
  - Mirror technology is not a driving concern

ExoPlanet Exploration Program

Example: GALEX (2003–present)
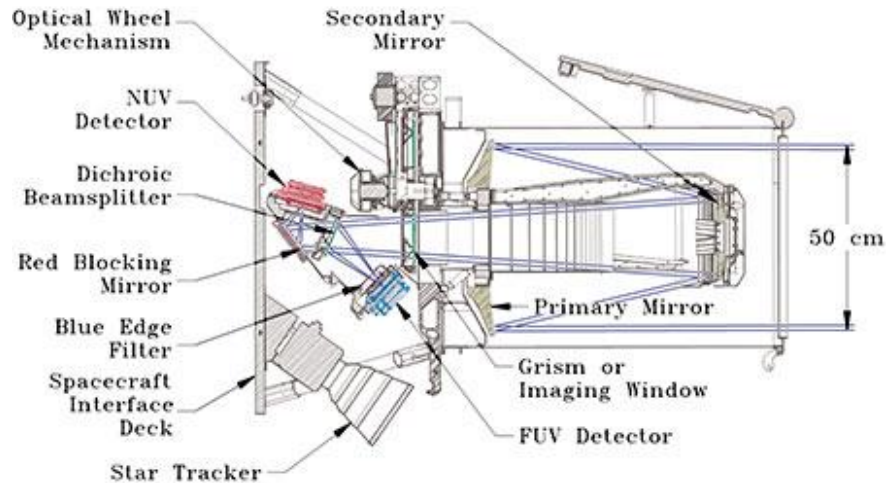
The most cost-effective way to improve sensitivity for a UV telescope would be to develop better UV detectors and more efficient coatings – not by going to larger mirrors

Exoplanet missions need mirrors at **least** 4-m in diameter

A starshade design would not impose additional constraints on a UV telescope, other than adding navigator beacons or sensors

A coronagraph design typically requires an **unobscured**, **off-axis primary**, and polarization-preserving **multi-layer coatings**, thus imposing numerous additional requirements on the telescope

ExoPlanet Exploration Program

- There are several possible approaches to designing exoplanet missions
  - Coronagraphs
  - Interferometers
  - Starshades

- Wavefront sensing and control is the central concern, not mirror size
  - Starlight suppression with deformable mirrors
  - Thermal and structural stability
  - Metrology for sensing and control

- Diffraction-limited 4-m class (or larger) primary mirror is needed to detect Earth-like planets
  - Surface figure similar to HST required
  - Stability tolerances of coronagraphs are achievable when larger primaries are used in conjunction with 8th-order masks
  - Smaller primary mirrors could be used with aggressive coronagraph designs, but the stability tolerances are then extremely challenging

- Long term vision for large telescope development includes space-based segmented-mirror telescopes using actively-controlled glass segments or silicon carbide hybrid-mirror designs

ExoPlanet Exploration Program

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

Backup

ExoPlanet Exploration Program

Lawson, Shaklan, and Balasubramanian

ExoPlanet Exploration Program

Visible Nulling Coronagraph

Phase Induced Amplitude Apodization 2λ/D

Vector Vortex 2.5λ/D

Shaped Pupil Mask 4λ/D

Band-limited Mask (Hybrid) 3λ/D

Band-limited Mask (Metallic) 4λ/D

Milestone 1 & 2 Requirement

Earth/Sun Contrast

Constrast (Background/Source)

Optical Bandwidth (percent)
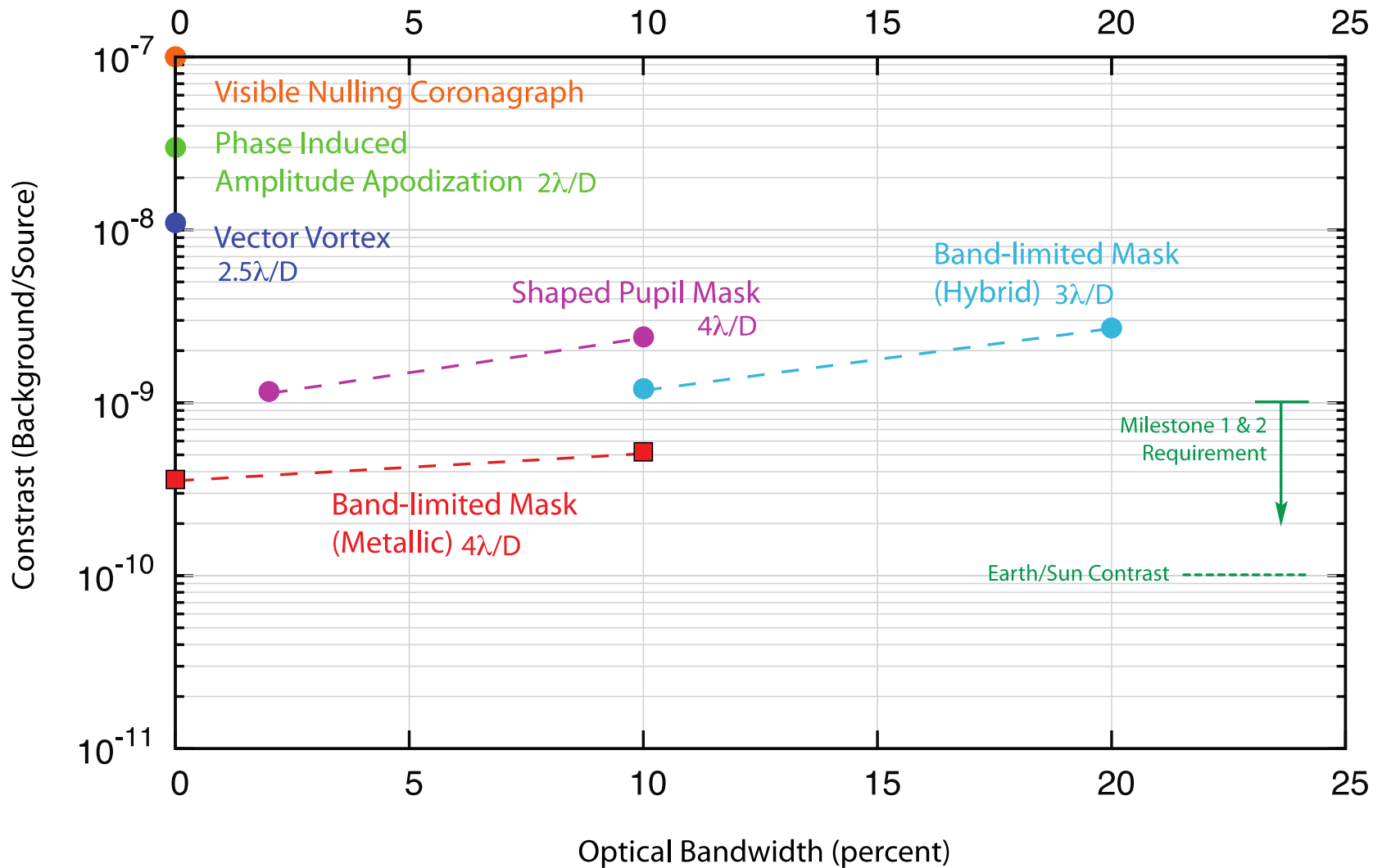
Coronagraph Low-order Aberration Sensitivity For 3.5 x 8.0-m Primary Mirror at 4λ/D

Allowed Root Mean Square Wave Front for Contrast = 1 x 10^{-12} at 4λ/D

3.5 x 8.0-m elliptical primary mirror

TPF-Coronagraph

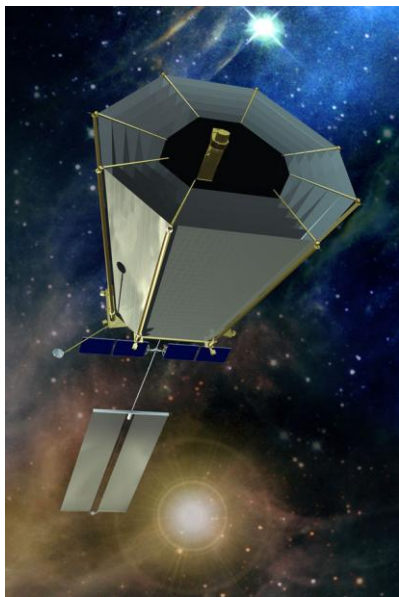| Aberration	Eight order mask	Fourth order mask	Relaxation Ratio
Tilt	3.764	0.236	16
Focus	0.333	0.003	132
Astigmatism	0.464	0.004	132
Coma	0.088	0.001	185
Trefoil	0.201	0.002	132
Spherical	0.003	4.0E-4	7.2

Note. – Aberration units are in nm rms

S. B. Shaklan and J. J. Green "Low-order aberration sensitivity of eighth-order coronagraph masks," Astrophysical Journal 628, 474-477 (2005), Table 1 rescaled for a wavelength of 550 nm.

ExoPlanet Exploration Program

ExoPlanet Exploration Program

BEAM Engineering for Advanced Measurements
686 Formosa Avenue
Winter Park, FL 32789-4523
Nelson Tabirian (407) 629-1282
10-1-S2.02-8374 JPL
Achromatic Vector Vortex Waveplates for Coronagraphy

Boston Micromachines Corporation
30 Spinelli Place
Cambridge, MA 02138-1070
Paul Bierden (617) 868-4178
10-1-S2.02-8461 JPL
Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

Iris AO, Inc.
2680 Bancroft Way
Berkeley, CA 94704-1717
Michael Helmbrecht (510) 849-2375
10-1-S2.02-9446 GSFC
Picometer-Resolution MEMS Segmented DM

Bridger Photonics Inc.
112 East Lincoln
Bozeman, MT 59715-6504
Randy Reibel (406) 585-2774
10-1-S2.03-8200 JPL
Multi-Point Trilateration: A New Approach for Distributed Metrology

Vanguard Composites Group, Inc.
9431 Dowdy Drive
San Diego, CA 92126-4336
Steven Sherman (858) 587-4210
10-1-S2.03-8698 JPL
*Carbon Fiber Reinforced, Zero CME Composites*

L'Garde, Inc.
15181 Woodlawn Avenue
Tustin, CA 92780-6487
Roger Garrett (714) 259-0771
10-1-S2.03-9177 JPL
Thermally-Stable High Strain Deployable Structures

Trex Enterprises Corporation
10455 Pacific Center Court
San Diego, CA 92121-4339
Deborah Doyle (858) 997-9508
10-1-S2.04-9269 MSFC
Silicon Carbide Corrugated Mirrors for Space Telescopes

ExoPlanet Exploration Program

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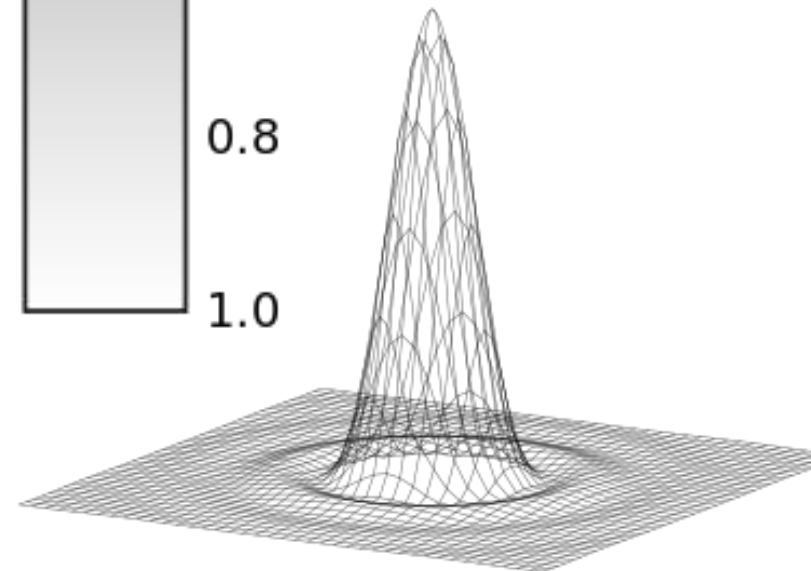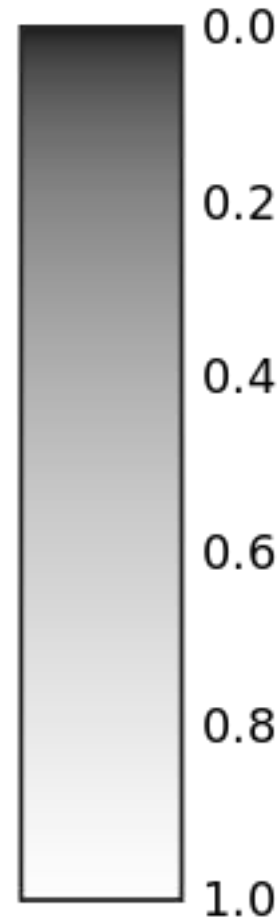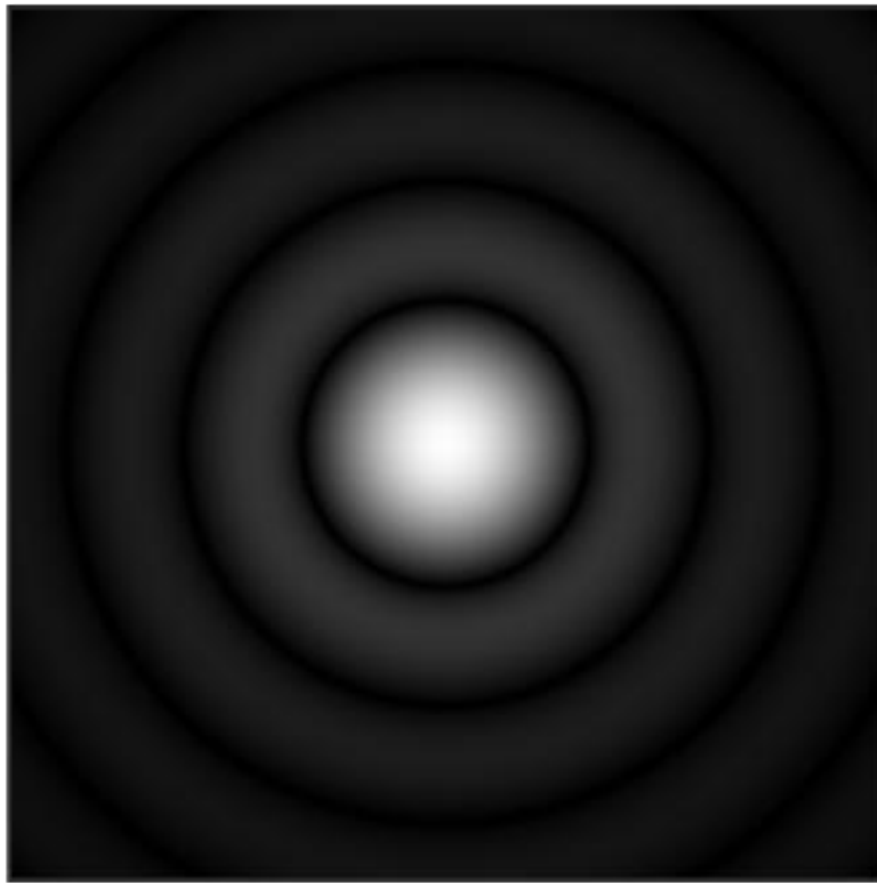
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